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Influence of Atmospheric Parameters on the Degradation of Solar Panels' Electrical Performance

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Abstract

The objective of this study was to examine the premature degradation of photovoltaic solar panels under the influence of atmospheric parameters (temperature, humidity, pressure, wind, irradiance, etc.), based on the key elements of Bishop's mathematical model (two-diode model). The Bishop mathematical model is one of the models that allows us to better describe and explain the behavior of these panels during operation, taking into account the geographical environment in which the solar cells are located. As a result, they are subject to various defects and anomalies that contribute to a decrease in efficiency. Using MATLAB software, we were able to plot and analyze the progression of degradation in electrical parameters (series and shunt resistances) on the power output of the solar panel. From the families of plotted curves, it is evident that the increase in series resistance and the decrease in shunt resistance are due to corrosion caused by humidity in the environment where the photovoltaic cell is located. Both of these analyzed cases significantly reduce the power output of the solar panel. A degradation coefficient for the series resistance was calculated, a value that is consistent with results reported in the literature.

Keywords

Atmospheric Parameters, Solar Panels, Photovoltaics, Series and Shunt Resistors

1. Introduction

A photovoltaic cell is a device that converts solar energy into electrical energy by absorbing photons and converting the energy of those photons into electrical energy. Renewable energy offers a real opportunity to meet energy needs while respecting environmental, social, economic, strategic, and ethical imperatives. Over the past few decades, air pollution, global warming, and the risks of nuclear power have raised awareness of the need for a societal structure that respects the environment, so that all actions are geared toward "sustainable development."

Of the five types of energy considered renewable (solar, wind, hydro, geothermal, and biomass), solar energy is the one without which the others could not exist. Through photovoltaic conversion, its light component is transformed into electrical energy using solar panels [1].

All of these adverse effects reduce the system's productivity and, consequently, its profitability, compounded by the maintenance costs required to ensure the system's optimal operation [1].

When installed in a given environment, a photovoltaic generator is subject to specific atmospheric conditions (humidity, temperature, rainfall, sunlight, pressure, etc.) that can degrade its properties sooner or later. These conditions affect the efficiency and even the lifespan of the solar cells. They vary depending on the geographic location and the seasons.

A PV cell under operating conditions cannot be considered an ideal diode and exhibits parasitic resistances in series (R_s) and in parallel (R_{sh}). These two types of resistance reduce the fill factor and, consequently, the power output of the cell [2].

The power output of solar modules decreases as series resistance increases and parallel resistance decreases. Studies have shown that increased humidity leads to an increase in the module's series resistance and, consequently, a decrease in the module's maximum power output [3].

The series resistance does not affect the open-circuit voltage but reduces the short-circuit current.

In [4]-[7], the performance of photovoltaic modules can be degraded due to factors such as temperature, humidity, irradiance, dust, and mechanical shocks.

These various factors can lead to one or more types of degradation, such as discoloration, delamination, corrosion, and cell breakage and cracking [5] [8]-[10].

Wolghemuth and Kurtz [11] studied the impact of humidity and temperature on the degradation of PV modules using 85/85 accelerated tests (T = 85˚C/RH = 85%) in accordance with IEC 61215. The solar modules were subjected to testing, and it was demonstrated that corrosion occurred after 1000 hours of exposure at a temperature of 85˚C and a relative humidity of 85%.

The findings from these tests on solar modules led [12]-[17] to conclude that corrosion was the most common form of degradation observed in photovoltaic modules.

Furthermore, [18]-[20] also stated that corrosion and discoloration are the predominant modes of degradation in photovoltaic modules; similarly, Jean-Pierre OUSTEN demonstrated that humidity is a major factor in corrosion at the edges of PV modules [21].

[22]-[24] described the aging of photovoltaic cells based on measurements taken by Hulkoff during a humid heat test at 85/85 RH for a sample of a monocrystalline silicon photovoltaic cell. From this experiment, Hulkoff measured a decrease in shunt resistance and an increase in series resistance.

Nausicaa Dornic *et al.* in [25] stated that moisture within photovoltaic modules has a significant impact on the degradation rate of photovoltaic modules, particularly in hot and humid regions.

Studies have shown that increased humidity leads to:

An increase in the module's series resistance and, consequently, a decrease in the module's maximum power [13]. Series resistance does not affect the open-circuit voltage but reduces the short-circuit current [13].

A decrease in shunt resistance often indicates the onset of degradation in the module [13]-[18]. The lower the shunt resistance, the greater the current flowing through it, and consequently, the lower the current produced by the module. The effect of shunt resistance results in a slight slope near the short-circuit point. In general, its value is very high. A solar cell with a shunt resistance that is too low will no longer produce voltage under low light conditions [6].

Thus, it was appropriate for us to evaluate the impact of atmospheric parameters (temperature, humidity, pressure, wind, irradiance, etc.) on the components of the photovoltaic generator model.

Among the types of degradation cited in the literature, in this article we focused on the effects of humidity, which causes corrosion that leads to a decrease in the efficiency of solar cells.

2. Methodology

2.1. Equivalent Electrical Circuit

The electrical behavior of a panel is modeled using the equivalent circuit shown in **Figure 1**, which consists of basic electrical components (source, resistor, diode, inductor, capacitor, etc.).

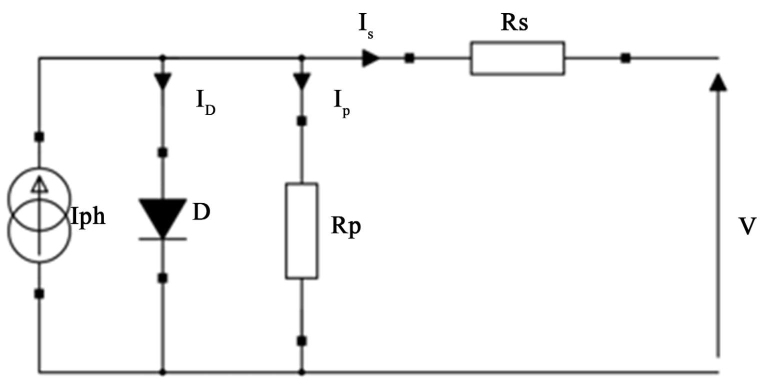

Figure 1. Simplified electrical diagram of a photovoltaic cell.

Experience shows that in the dark, a solar cell behaves like a regular diode, start-

ing to conduct when the applied voltage is higher than the threshold voltage V_s.
In the case of an ideal cell:
in the dark, the $I = f(V)$ characteristic is represented by the relation (1):

$$I_D = I_{obs} = I_{S1} * \left[e^{\frac{(V+R_S*I)}{n*V_t}} - 1 \right] \quad (1)$$

where:

$$I_{S1} = K_1 T^3 * e^{\frac{-Eg}{KT}}$$

under illumination, the thermal tension at temperature T: $V_t = \frac{KT}{q}$.

q: is the charge of the electron; K, Boltzmann constant;
K_1, Constant (1.2 A/cm²K³);
n_1, Junction ideality factor;
T, Effective cell temperature (K);
Eg, Bandgap energy (1.12 eV for crystalline silicon).

$$I_{ph} = I_D + I + I_{R_P} \quad (2)$$

Under illumination, the equivalent electrical circuit of a photovoltaic cell is represented by the following equation:

$$I = I_{Ph} - I_{S1} * \left[e^{\left(\frac{V+R_S*I}{n_1*V_t}\right)} - 1 \right] - \left(\frac{V + R_S I}{R_P} \right) \quad (3)$$

In the case of a real photovoltaic cell, other factors are taken into account, such as resistive effects and edge leakage [26].

The principle behind the photovoltaic effect is essentially that of a diode; thus, when light is shone on the PN junction—with the cell connected to a resistor—a current I flows through the load R_{ch}, and a voltage "V" appears across that load. This description leads us to the equivalent electrical model of the photovoltaic cell—known as the ideal model—which accounts only for the phenomenon of diffusion. To account for the material's resistivity and ohmic losses due to the contacts, and to better represent the cell's electrical behavior relative to the ideal model, these voltage drops are represented by a series resistance R_s and the leakage currents by a parallel resistance R_p in the equivalent circuit.

The actual behavior of the solar cell takes into account the mechanism of charge transfer within the cell; an additional diode is used in the equivalent circuit to reproduce the chemical effects of electron recombination. In a real solar cell, recombination represents a significant loss that cannot be adequately modeled using a single diode. Accounting for this loss results in a more accurate model known as the two-diode model.

The ideality factor of a diode is thus a dimensionless parameter that measures the deviation between the actual behavior of a PN junction and its ideal theory. Its value generally ranges between 1 and 2, depending on the dominant conduction mechanisms. The saturation current corresponds to the flow of thermally generated minority carriers that traverse the depletion region under the influence of the electric field. It appears as a multiplier in Shockley's formula relating the current I_d to the voltage V_d.

2.2. Bishop Model

The complete characteristic of the photovoltaic cell is obtained from the Bishop model, called the two-diode model, thanks to the insertion of a second diode in parallel with the first series diode, as shown in Figure 2.

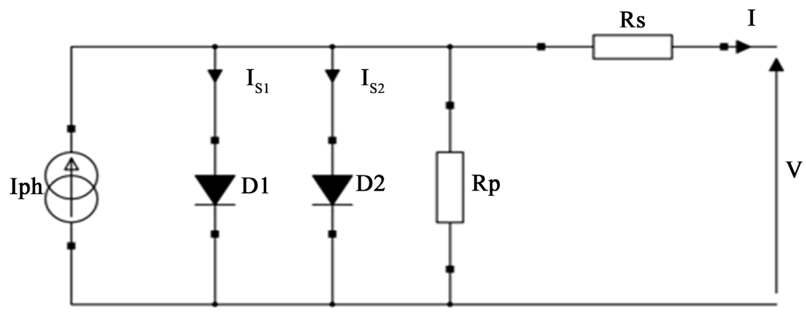

Figure 2. Two-diode model.

The equation of this model is written as follows [7]

$$I = I_{Ph} - I_{S1} * \left[e^{\left(\frac{V + R_S * I}{n_1 * V_t}\right)} - 1 \right] - I_{S2} * \left[e^{\left(\frac{V + R_S * I}{n_2 * V_t}\right)} - 1 \right] - \frac{(V + R_S * I)}{R_P} \quad (4)$$

With

$$I_{Ph} = I_{Pho} X \frac{I_r}{I_o}$$

where I_r is the light intensity shining on the cell (Wm^{-2}); I_o, the intensity under standard conditions (1000 Wm^{-2}); and I_{pho}, the photocurrent measured under standard conditions. Based on the characteristics shown in Table 1 of the solar panel, we analyzed:

- The influence of humidity on the resistive parameters (R_s and R_p) of the mathematical model of the solar panel with two diodes (Bishop model);
- The influence of irradiation and temperature on the power delivered by a solar module.

Since the two resistors do not degrade according to the same pattern, it was not easy for us to vary both parameters at the same time. To address this, we decided to work under a specific assumption: keeping one parameter constant while varying the other, and vice versa.

Furthermore, we opened up new avenues for exploring how we might vary both parameters simultaneously and, in doing so, better assess the degradation associated with changes in these two parameters.

For these simulations, we focused on the parameters that degrade the performance

Table 1. The values of the different characteristic quantities of the solar panel used in this work.

Description	Values
Short-circuit current	$I_{sc} = 4.8$ A
Open-circuit voltage	$V_{oc} = 43.4$ V
Current at maximum power point	$I_{mp} = 4.4$ A
Voltage at maximum power point	$V_{mp} = 34$ V
Power at maximum power point	150 W
Saturation current	$I_o = 6.97410^{-8}$ A
Photo current	$I_{ph} = 4.807$A
Series resistance	$R_s = 0.67\ \Omega$
Parallel resistance	$R_p = 466.4639\ \Omega$
The elementary charge of a particle	$q = 1.610^{-19}$ C
Boltzmann constant	$K = 1.3810^{23}$
Index	$n = 1.3$

of photovoltaic solar modules, namely temperature and series and shunt resistances. Therefore, irradiance remained constant throughout these simulations.

3. Results

In this section, we present the different results of the simulations.

3.1. Influence of Irradiation and Temperature

- The current-voltage characteristic at different values of irradiation.
- the current-voltage characteristic at different temperature values.

Figure 3 and Figure 4 show the influence of sunlight on the output power of the photovoltaic module. The short-circuit current increases proportionally with the level of incident light, while the open-circuit voltage increases logarithmically with illumination. As a result, there is a strong influence of sunlight on the current delivered by the solar cell. This effect leads to an increase in the power delivered when the light intensity rises, hence an increase in the maximum power the cell can provide.

Figure 5 and Figure 6 show how power varies with voltage for different temperature values. Rising temperatures lower efficiency because the electrical components of a semiconductor are very sensitive to heat.

The power of solar modules drops as the series resistance goes up and the parallel resistance goes down. Studies have shown that higher humidity increases the module’s series resistance, which in turn reduces the module's maximum power.

Series resistance doesn’t affect the open-circuit voltage but does reduce the short-circuit current.

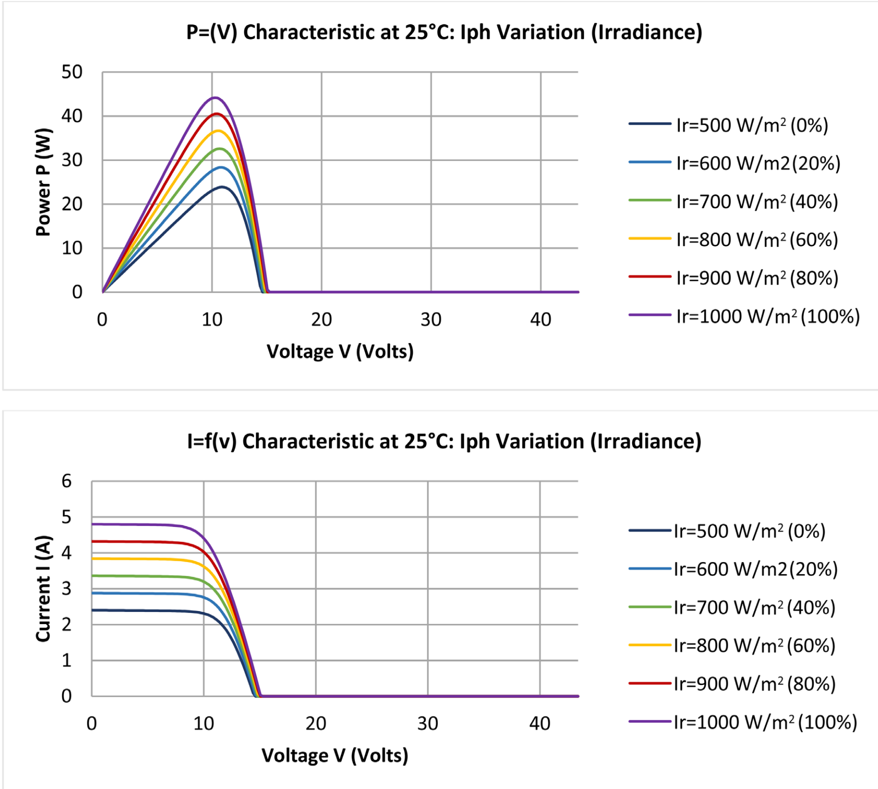

Figure 3. Power characteristic as a function of voltage and current characteristic as a function of voltage at different radiation values at 25˚C.

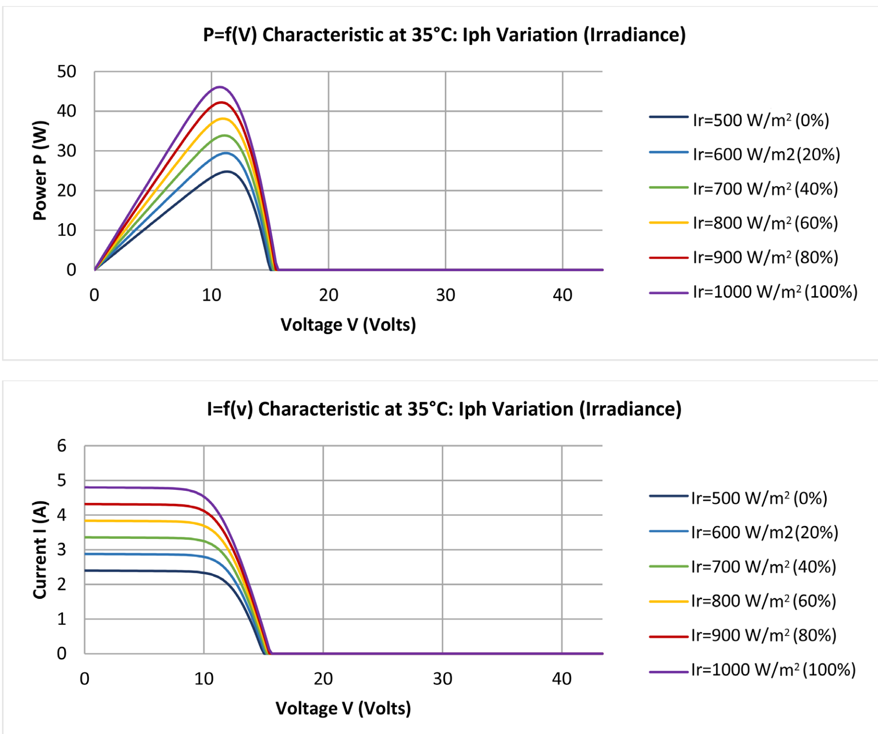

Figure 4. Power characteristic as a function of voltage and current characteristic as a function of voltage at different radiation values at 35˚C.

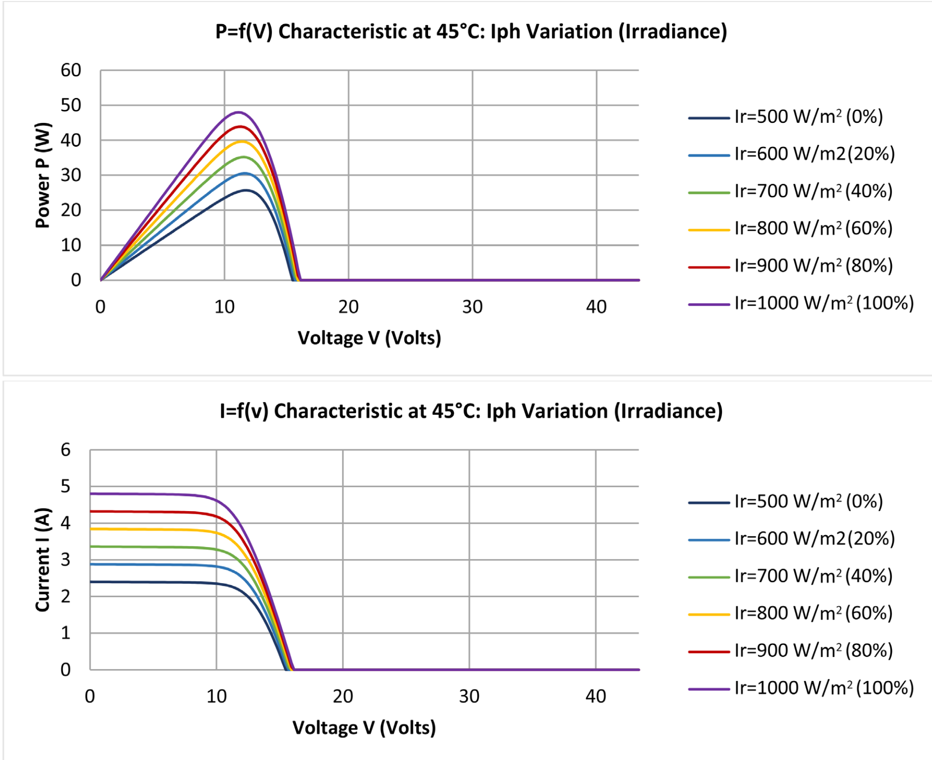

Figure 5. Power characteristic as a function of voltage and current characteristic as a function of voltage at different radiation values at 45˚C.

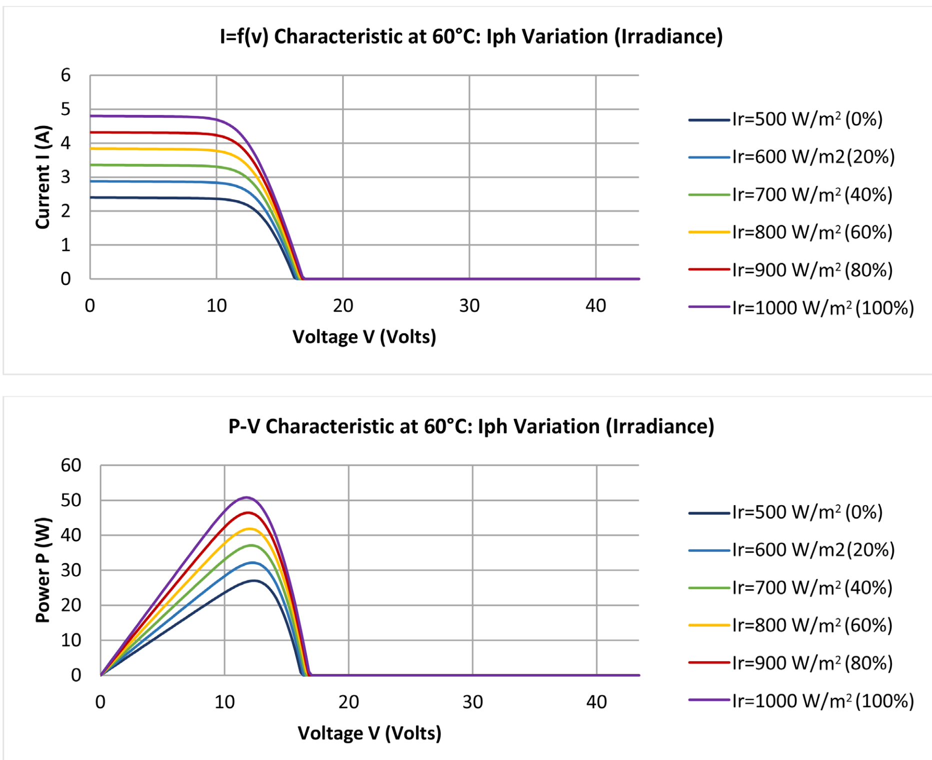

Figure 6. Power characteristic as a function of voltage and current characteristic as a function of voltage at different radiation values at 60˚C.

3.2. Influence of Humidity on R_s and R_p

By taking into account the terms of Equation (4), it's pretty clear to see how weather data (temperature, humidity, sunlight, wind, pressure, etc.) affects the different electrical parameters (series resistance: R_s and shunt resistance: R_p) of solar modules.

3.2.1. Influence of Humidity on Series Resistance R_s

Table 2 shows the different values of series resistance and the values of the degradation percentages.

Table 2. Different values of series resistance at different percentages.

R_s (Ω)	0.67	0.804	0.938	1.072	1.206	1.34
% of degradation	0	20	40	60	80	100

Figures 7-12 show the current-voltage curve characteristics for the values of series resistance R_s obtained by increasing the base value (initial value) of the series resistance by 20%, 40%, 60%, 80%, and 100% and at different temperatures (25˚C, 35˚C, and 45˚C). From these families of curves, we can better understand the effect of increasing series resistance on the degradation (reduction) of the output power delivered by a solar panel during its operation.

From the evolution of these sets of curves, we have just confirmed the claims of [13] and [18] about the effect of humidity on solar panels, which causes corrosion and thus leads to an increase in series resistance, and consequently, the degradation of the solar panels that ends up reducing their power. These sets of curves support the theory developed by researchers based on long-term observational experience.

Moisture buildup affects solar panels. It can lead to reduced performance, condensation, or promote corrosion of components, particularly electronic components.

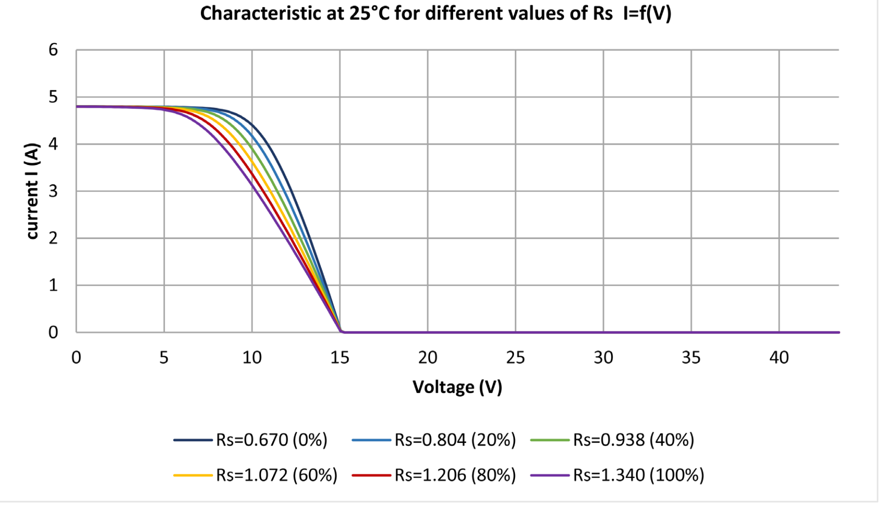

Figure 7. Current-voltage characteristic as a function for different values of the series resistance at 25˚C.

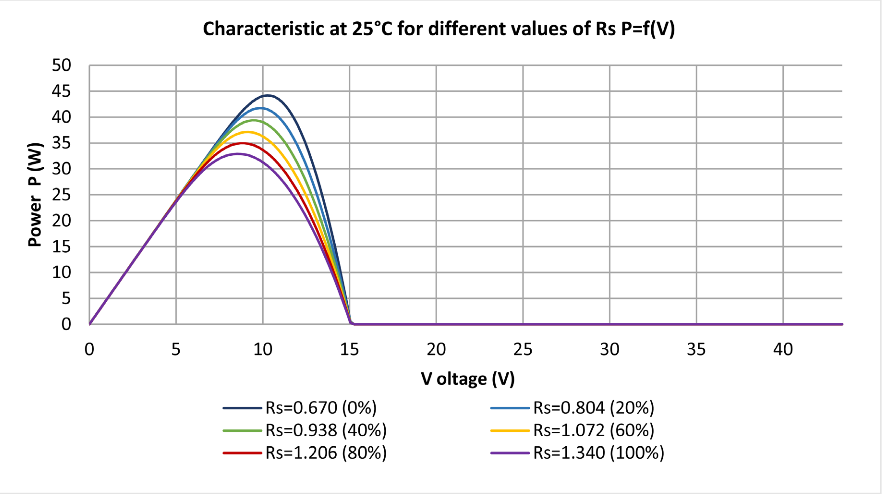

Figure 8. Current-voltage characteristic of the power as a function for different values of series resistance at 25˚C.

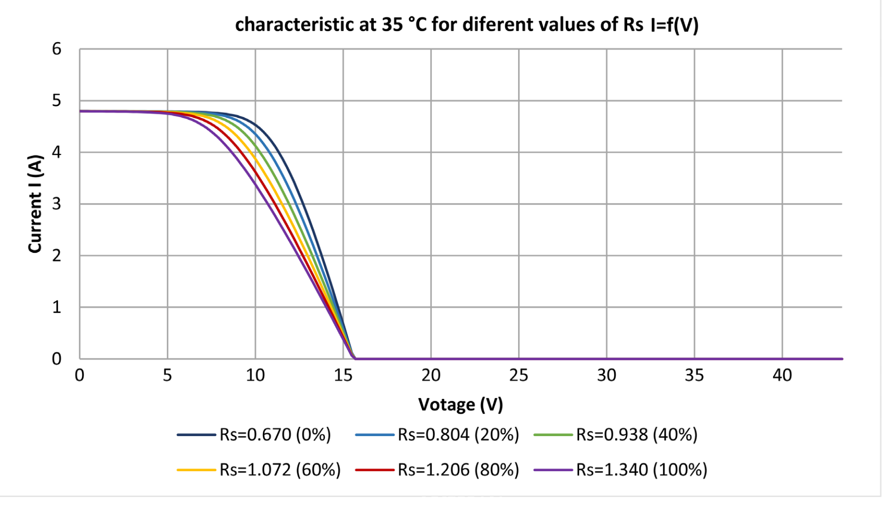

Figure 9. Current-voltage characteristic of the power as a function for different values of series resistance at 35˚C.

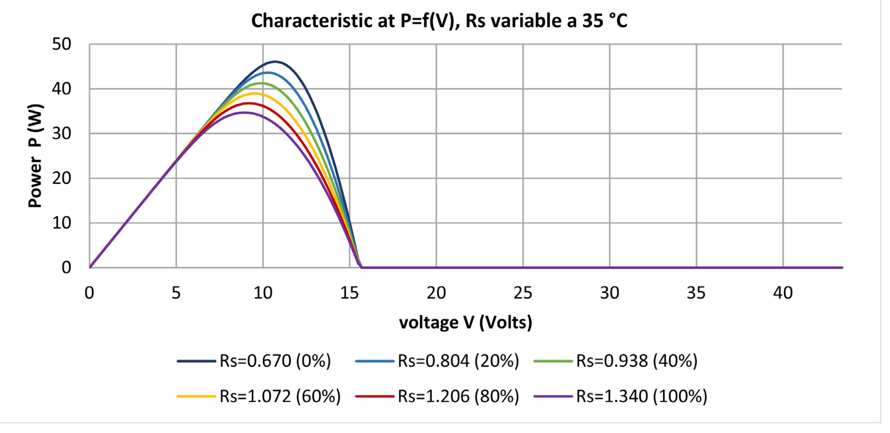

Figure 10. Current-voltage characteristic of the power as a function for different values of series resistance at 35˚C.

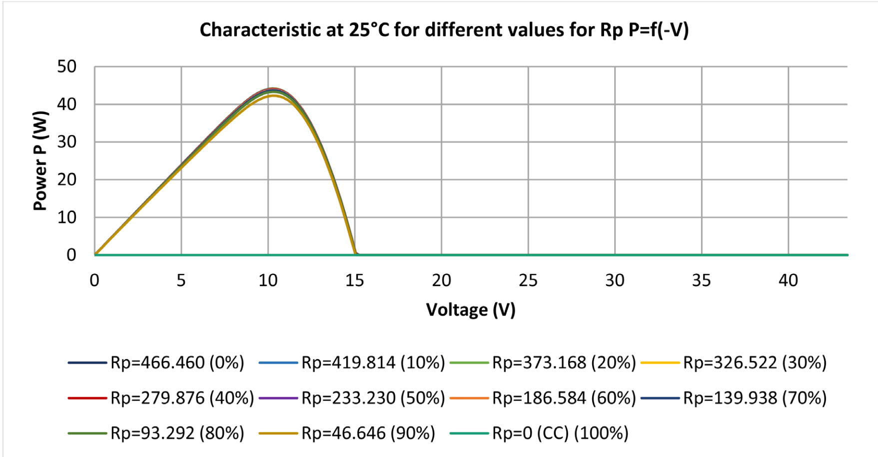

Figure 11. Power-voltage characteristic as a function for different values of the shunt resistor at 25˚C.

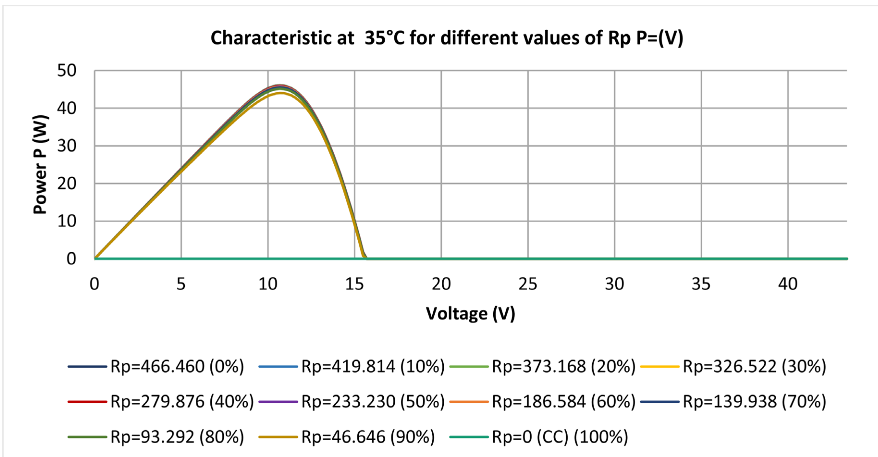

Figure 12. Power-voltage characteristic as a function for different values of the shunt resistor at 35˚C.

Moisture penetration into the module—through the backsheet or along the module edges—causes corrosion or oxidation of the metal contacts, thereby increasing the series resistance (RS) [12].

3.2.2. Influence of Humidity on R_P Resistance

Table 3 shows the different values of the shunt resistance and the values of degradation percentages.

Table 3. Different values of the shunt resistance at different percentages.

R_P	466.46	419.814	373.168	326.522	279.876	233.23	186.584	139.938	93.292	46.646	0
%	0	10	20	30	40	50	60	70	80	90	100

Figures 11-13 show the characteristics of the current-voltage curve family for the values of resistance R_p obtained by reducing the base (initial) value of the shunt resistance by (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%)

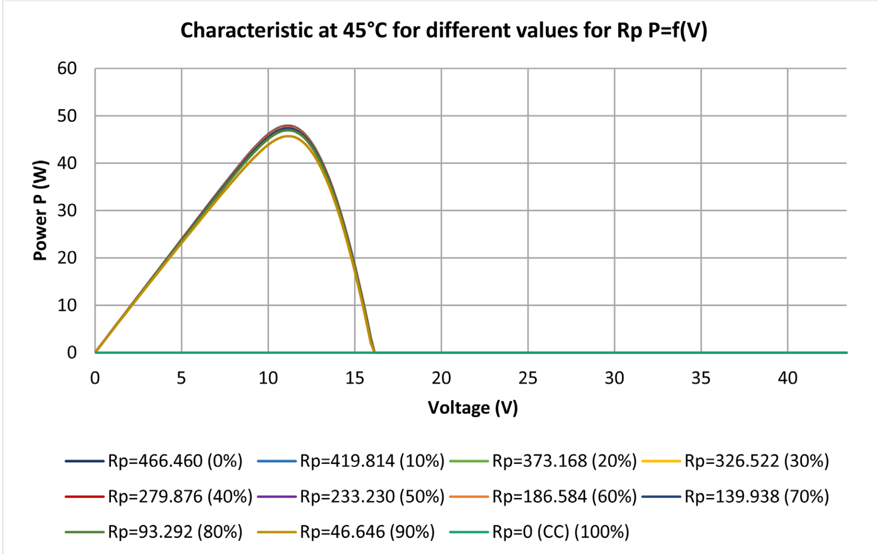

Figure 13. Current-voltage characteristic as a function for different values of the shunt resistance at 45˚C.

and at different temperature values (25˚C, 35˚C, and 45˚C). From these families of curves, we can better understand the effect of reducing the shunt resistance on the degradation (decrease) of the output power delivered by a solar panel during its operation.

Looking at the analysis of the different curves, it becomes clear that the increase in series resistance over time leads more to the degradation of a solar panel's output power compared to the effect of the decrease in shunt resistance over time. It's necessary to define a relationship between these two characteristic values of the panel in order to better understand their influence on the panel's degradation. In this article, this influence was observed independently. Defining the relationship between these two values (R_s and R_p) in the design of the mathematical model would be the key factor whose variation would allow for a better tracking of the solar panel's degradation over time and, consequently, of these values in relation to the impact of atmospheric parameters on the solar panel's lifespan.

3.3. Effect of Resistance on the Lifespan of Solar Cells

Based on the characteristics of the solar cell used, experimental data show that for an operating life of the solar cell of 25 years, the series resistance R_s increases by 5%, the shunt resistance decreases by 74%, and the transmittance drops by about 10% [22].

Based on this experimental data, we were able to plot, from the characteristics of the panel used, the curves representing the decrease and increase of the shunt resistance and series resistance, respectively. This allowed us to deduce the law of the evolution of this panel degradation over time, covering a period of 25 years. These curves show that the increase in series resistance over time grows linearly according to the law of Equation (5), with a slope of 0.00134.

$$R_S(t) = 0.00134t + 0.67 \quad (5)$$

This result is similar to that obtained by [24], whose slope is 0.00122 for a series resistance panel of 0.53 Ω. On the other hand, the decrease in the shunt resistance does not follow a linear decline (Equation (6)).

$$R_P(t) = 0.01826t^2 - 2.3239t + 466.46 \quad (6)$$

Based on the characteristic data of the solar panel, the curves in Figure 14 and Figure 15 show over a 25-year period, respectively, the increase in series resistance and the decrease in shunt resistance.

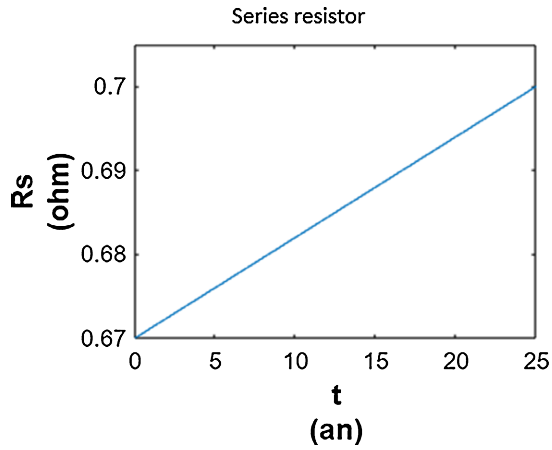

Figure 14. The change in series resistance over time.

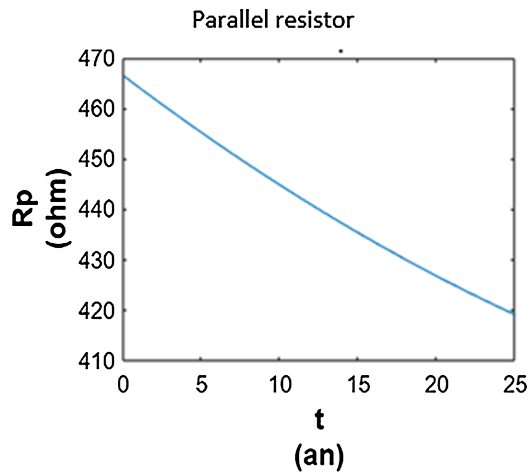

Figure 15. The variation of the shunt resistance over time.

4. Analysis of Results

Looking at the different ways solar cells degrade presented in this work, it turns out that corrosion is one of the modes that shows up due to the influence of factors like humidity, since humidity affects and destroys the characteristic elements of the mathematical model. Modeling the solar module allows us to calculate the current it delivers to the grid. Two key features of this model, namely the series and parallel resistances, are impacted by humidity, with the series resistance increasing and the shunt resistance decreasing.

In this article, we illustrated the effect of increasing the series resistance on the output power delivered by the module. The set of curves shown demonstrates that the output power of the module decreases gradually as the series resistance increases. This is because the point of maximum power the module can deliver shifts according to the module's characteristics as designed by the manufacturer. This observation also applies to the set of curves affected by the decrease in shunt resistance.

This simulation was done separately. It would be wise to vary both parameters at the same time to better assess the final degradation in the power delivered by the module. This wasn't easy in the context of this work, because you need to know the degradation rate of both parameters under the influence of a single atmospheric factor. The correlation of the impact of degradation between these two parameters will need to be defined. Under the effect of humidity, the degradation of these two parameters doesn't follow the same pattern. During this degradation, the series resistance increases linearly, whereas the decrease in shunt resistance is not linear.

With the characteristics of the module used for simulation reasons, the laws governing the degradation of these two resistances were established over the 25-year period corresponding to the estimated lifespan of the module.

5. Conclusions

Environmental, mechanical, chemical, thermal, and electrical factors each lead to different modes of degradation in solar panels. Prolonged exposure to humidity causes material aging, which consequently reduces efficiency.

The degradation of solar cells is related to the destruction of their constituent elements. These elements remain sensitive to atmospheric conditions. In this work, we focused on the mathematical equation that models the solar panel. The analysis of the overall panel degradation was based on the behavior of each of the panel's components in relation to the atmospheric parameters of the environment where the panel would be placed. Thus, the influence of temperature and humidity on the degradation of the solar panel was the main focus of this study.

Based on the results from the literature and starting from the Bishop model equation, we were able to check the influence of humidity on the series and shunt resistances. Humidity causes the series resistance to increase and the shunt resistance to decrease. The behavior of these two quantities (series and shunt resistances) was analyzed independently, but it would make sense to look at how the output power degrades as a result of the combined degradation of these two characteristics of the Bishop model and, consequently, establish a degradation law that would include both quantities. It turns out that the degradation of these aforementioned quantities doesn't follow the same rule. The series resistance degrades linearly, whereas the shunt resistance degrades non-linearly.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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